Light

Visible electromagnetic radiation

Power spectrum

Polarization

Photon (quantum effects)

Wave (interference, diffraction)

Topics

Light sources and illumination

Radiometry and photometry

Quantify spatial energy distribution

- Radiant intensity
- Irradiance
  - Inverse square law and cosine law
- Radiance
- Radiant exitance (radiosity)

Illumination calculations

- Irradiance from environment
Radiometry and Photometry

Radiant Energy and Power

Power: Watts vs. Lumens
- Energy efficiency
- Spectral efficacy

Energy: Joules vs. Talbot
- Exposure
  - Film response
  - Skin - sunburn

\[ Y = \int V(\lambda)L(\lambda)d\lambda \]
Radiometry vs. Photometry

Radiometry [Units = Watts]
- Physical measurement of electromagnetic energy

Photometry and Colorimetry [Lumen]
- Sensation as a function of wavelength
- Relative perceptual measurement
  \[ B = Y^2 \]

Brightness [Brils]
- Sensation at different brightness levels
- Absolute perceptual measurement
- Obey Steven's Power Law

Blackbody Radiation

*FIGURE 21F*
Blackbody radiation curves plotted to scale. Ordinates give the energy in calories per square centimeter per second in a wavelength interval of 1 Å. For numerical values, see “Smithsonian Physical Tables,” 8th ed., p. 314.
**Tungsten Lamp**

![Graph showing the radiant characteristics of tungsten.](Image)

Fig. 8-1. Radiating characteristics of tungsten. Curve A: radiant flux from one square centimeter of a black body at 3000 K. Curve B: radiant flux from one square centimeter of tungsten at 3000 K. Curve B': radiant flux from 2.27 square centimeters of tungsten at 3000 K (equal to curve A in visible region). (The 500-watt 120-volt general service lamp operates at about 3000 K.)

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**Fluorescent Bulb**

![Diagram of a fluorescent bulb.](Image)

Fig. 3(1.23). Relative spectral radiant power distributions of common fluorescent lamps: (1) standard warm white; (2) white; (3) standard cool white; and (4) daylight. The distribution curves have been scaled by appropriate constant factors to provide a common value of 100 at \( \lambda = 560 \text{ nm} \).
Sunlight

Fig. 11.2(b). NASA standard data of spectral irradiance (W m$^{-2}$ $\mu$m$^{-1}$) for the solar disk measured outside the atmosphere (solid line) and at the earth's surface at sea level (open circles). Data points are those given in Table 11.2(b). Neighboring data points have been connected by straight lines for illustrative purposes only.
Radiant Intensity

**Definition:** The radiant (luminous) intensity is the power per unit solid angle emanating from a point source.

\[ I(\omega) \equiv \frac{d\Phi}{d\omega} \]

\[
\left[ \frac{W}{sr} \right] \left[ \frac{lm}{sr} = cd = \text{candela} \right]
\]

---

The Invention of Photometry

**Bouguer’s classic experiment**
- Compare a light source and a candle
- Move until they both appear equally bright
- Intensity is proportional to ratio of distances squared

**Definition of a candela**
- Originally a “standard” candle
- Currently 550 nm laser w/ 1/683 W/sr
- 1 of 6 fundamental SI units
Angles and Solid Angles

- **Angle** \( \theta = \frac{l}{r} \)

  \( \Rightarrow \) circle has \( 2\pi \) radians

- **Solid angle** \( \Omega = \frac{A}{R^2} \)

  \( \Rightarrow \) sphere has \( 4\pi \) steradians

Differential Solid Angles

\[
dA = (r \, d\theta)(r \sin \theta \, d\phi) = r^2 \sin \theta \, d\theta \, d\phi
\]

\[
d\omega = \frac{dA}{r^2} = \sin \theta \, d\theta \, d\phi
\]
**Differential Solid Angles**

\[ \Omega = \int_{S^2} d\omega \]
\[ = \int_0^\pi \int_0^{2\pi} \sin \theta \, d\theta \, d\phi \]
\[ = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_{-\pi}^{\pi} d\cos \theta \, d\phi \]
\[ = 4\pi \]

**Isotropic Point Source**

\[ \Phi = \int_{S^2} I \, d\omega \]
\[ = 4\pi I \]

\[ I = \frac{\Phi}{4\pi} \]
Warn’s Spotlight

\[ \Phi = \int_0^{2\pi} \int_0^1 I(\omega) d\cos \theta d\phi \]

\[ I(\omega) = \Phi \frac{s + 1}{2\pi} \cos^s \theta \]
Light Source Goniometric Diagrams

1. Porcelain-enamed ventilated standard done with incandescent lamp
2. Concentric ring unit with incandescent shielded bowl lamp
3. Pendant diffusing sphere with incandescent lamp

PIXAR Light Source

UberLight()
{
  Clip to near/far planes
  Clip to shape boundary
  foreach superelliptical blocker
    atten *= ...
  foreach cookie texture
    atten *= ...
  foreach slide texture
    color *= ...
  foreach noise texture
    atten, color *= ...
  foreach shadow map
    atten, color *= ...
  Calculate intensity fall-off
  Calculate beam distribution
}

Shadows
Shadow Matte
Projected Slide Texture
Radiance

Definition: The surface radiance (luminance) is the intensity per unit area leaving a surface

\[
L(x, \omega) \quad \frac{dI(x, \omega)}{dA} \quad \frac{d^2 L(x, \omega)}{d \omega \, dA}
\]

\[
\frac{W}{sr \, m^2} \quad \frac{cd}{m^2} \quad \frac{lm}{sr \, m^2} \quad \text{nit}
\]
Typical Values of Luminance [cd/m²]

<table>
<thead>
<tr>
<th>Surface of the sun</th>
<th>2,000,000,000 nit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunlight clouds</td>
<td>30,000</td>
</tr>
<tr>
<td>Clear day</td>
<td>3,000</td>
</tr>
<tr>
<td>Overcast day</td>
<td>300</td>
</tr>
<tr>
<td>Moon</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Radiant Exitance (Radiosity)
Radiant Exitance

**Definition:** The radiant (luminous) exitance is the energy per unit area leaving a surface.

\[ M(x) \equiv \frac{d\Phi_o}{dA} \]

\[ \begin{bmatrix} \frac{W}{m^2} \\ \frac{lm}{m^2} = \text{lux} \end{bmatrix} \]

In computer graphics, this quantity is often referred to as the *radiosity* \((B)\)

---

Area Light Source

\[ d^2 \cdot L_o(x, \theta) \cos \theta \cdot dAd \]

\[ d^2 \cdot L_o(x, \theta) \cos \theta \cdot dA \]

Same \(dA\) for all directions
Directional Power Leaving a Surface

$$\int L_o(x, ) \, dA$$

$$d^2 \cdot (x, ) \cdot L_o(x, ) \cos \, dAd$$

Uniform Diffuse Emitter

$$M = \frac{L_o \cos \, d}{H^2}$$

$$L_o \cos \, d$$

$$H^2 \text{ Hemisphere}$$
Projected Solid Angle

\[ \tilde{\Omega} \equiv \int_{\Omega} \cos \theta \, d\omega \]

\[ \sim \cos \theta \, d\omega \]

Uniform Diffuse Emitter

\[ M \quad L_o \cos d \]

\[ \frac{L_o \cos d}{H^2} \]

\[ \frac{L_o}{H^2} \]

\[ \frac{L_o}{M} \]
Irradiance

**Definition:** The irradiance (illuminance) is the power per unit area incident on a surface.

\[ E(x) \frac{di}{dA} \]

\[ \left[ \frac{W}{m^2} \right] \left[ \frac{lm}{m^2} = lux \right] \]

Sometimes referred to as the radiant (luminous) incidence.
Lambert’s Cosine Law

\[ \Phi = EA \]

\[ E = \frac{\Phi}{A} \]

---

Lambert’s Cosine Law

\[ \Phi \]

\[ A \quad A / \cos \theta \]

\[ \theta \]

\[ E = \frac{\Phi}{A / \cos \theta} = \frac{\Phi}{A} \cos \theta \]
Irradiance: Isotropic Point Source

\[ I = \frac{\Phi}{4\pi} \]

\[ d\Phi = I\ d\omega \]
Irradiance: Isotropic Point Source

\[ I = \frac{\Phi}{4\pi} \]

\[ d\omega = \frac{\cos \theta}{r^2} dA \]

\[ I \ d\omega = \frac{\Phi}{4\pi} \frac{\cos \theta}{r^2} dA \]
Irradiance: Isotropic Point Source

\[ I = \frac{\Phi}{4\pi} \]

\[ I \, d\omega = \frac{\Phi}{4\pi} \frac{\cos \theta}{r^2} \, dA = E \, dA \]

\[ E = \frac{\Phi}{4\pi} \frac{\cos \theta}{r^2} \]

\[ E = \frac{\Phi}{4\pi} \frac{\cos \theta}{r^2} = \frac{\Phi}{4\pi} \frac{\cos^3 \theta}{h^2} \]
## Typical Values of Illuminance [lm/m²]

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Illuminance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunlight plus skylight</td>
<td>100,000 lux</td>
</tr>
<tr>
<td>Sunlight plus skylight (overcast)</td>
<td>10,000</td>
</tr>
<tr>
<td>Interior near window (daylight)</td>
<td>1,000</td>
</tr>
<tr>
<td>Artificial light (minimum)</td>
<td>100</td>
</tr>
<tr>
<td>Moonlight (full)</td>
<td>0.02</td>
</tr>
<tr>
<td>Starlight</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

## Irradiance from the Environment

\[
d^2_i(x, \omega) L_i(x, \omega) \cos \theta dA \, d\omega
\]

\[
dE(x, \omega) = L_i(x, \omega) \cos \theta \, d\omega
\]

\[
E(x) = \int_{H^2} L_i(x, \omega) \cos \theta \, d\omega
\]
Directional Power Arriving at a Surface

\[ L_i(x, \omega)\]

\[ d^2\Phi_i(x, \omega) = L_i(x, \omega)\cos \theta dAd\omega \]

The Sky Radiance Distribution

From Greenler, Rainbows, halos and glories
Gazing Ball $\Rightarrow$ Environment Maps

Miller and Hoffman, 1984

- Photograph of mirror ball
- Maps all spherical directions to a circle
- Reflection direction indexed by normal
- Resolution function of orientation

Environment Maps

*Interface, Chou and Williams (ca. 1985)*
Irradiance Environment Maps

\[ L(\theta, \phi) \quad E(\theta, \phi) \]

Radiance Environment Map  Irradiance Environment Map

Irradiance Map or Light Map

Isolux contours
Radiometry and Photometry
Summary

Radiometric and Photometric Terms

<table>
<thead>
<tr>
<th>Physics</th>
<th>Radiometry</th>
<th>Photometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Radiant Energy</td>
<td>Luminous Energy</td>
</tr>
<tr>
<td>Flux (Power)</td>
<td>Radiant Power</td>
<td>Luminous Power</td>
</tr>
<tr>
<td>Flux Density</td>
<td>Irradiance</td>
<td>Illuminance</td>
</tr>
<tr>
<td></td>
<td>Radiosity</td>
<td>Luminosity</td>
</tr>
<tr>
<td>Angular Flux Density</td>
<td>Radiance</td>
<td>Luminance</td>
</tr>
<tr>
<td>Intensity</td>
<td>Radiant Intensity</td>
<td>Luminous Intensity</td>
</tr>
</tbody>
</table>
## Photometric Units

<table>
<thead>
<tr>
<th>Photometry</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MKS</td>
</tr>
<tr>
<td>Luminous Energy</td>
<td>Talbot</td>
</tr>
<tr>
<td>Luminous Power</td>
<td>Lumen</td>
</tr>
<tr>
<td>Illuminance</td>
<td>Lux</td>
</tr>
<tr>
<td>Luminosity</td>
<td>Nit</td>
</tr>
<tr>
<td>Luminance</td>
<td>Apostilb, Blondel</td>
</tr>
<tr>
<td>Luminous Intensity</td>
<td>Candela (Candle, Candlepower, Carcel, Hefner)</td>
</tr>
</tbody>
</table>

"Thus one nit is one lux per steradian is one candela per square meter is one lumen per square meter per steradian. Got it?", James Kajiya